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Design of integrated scanning laser Doppler velocitmeter using arrayed waveguide gratings

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Abstract

An integrated scanned differential LDV has been proposed using planar lightwave circuit (PLC) technology. By using the proposed LDV, the measurement position can be scanned in depth direction without any mechanical movement. The PLC technology is utilized in the proposed design for achieving a compact optical circuit. The characteristics of the proposed LDV are simulated with a design model based on grating equations for AWGs. The simulation result reveals that the measurement position can be changed over the range of 46 mm in the depth direction without mechanical movement when the displacement between output sides of two waveguide arrays is 30 mm.

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Keywords: Integrated optics; Laser Doppler velocimeter; Optical planar waveguides; Waveguide arrays; Precision measurement

1. Introduction

Velocity measurement has been widely used in researches and industries to measure the velocity of a fluid flow or rigid object. The velocity measurement using differential laser Doppler velocimeter (LDV) has several advantages of contactless, small measuring volume giving an excellent special resolution, and a linear response [1].

In the velocity measurement, measuring the distribution of velocity in depth direction should be needed in some applications such as fluid flow in narrow pipes or metal rolling process. In this case, the measurement position (measurement volume) in depth direction should be scanned. Several methods for scanning the measurement position using mechanical movement have been proposed [2,3]. However, the use of the mechanical movement needs special care for reducing failures.

Meanwhile, conventional LDVs using bulk optical system or fibers have large sizes and complexity of assembly, and are often affected by environmental disturbances, such as vibration, due to large optical path length in the

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optical system. Thus, integrated LDVs with high precision and small size have been highly demanded. Several types of integrated differential LDVs have been reported [4,5] as applications of integrated optical sensors. The authors have proposed [6] a design of an integrated wavelength-insensitive differential LDV based on planar lightwave circuit (PLC) technology [7-20]. As measurement position is still fixed in these types, an integrated differential LDV in which the measurement position can be changed is highly attractive.

In this paper, a design of an integrated scanned differential LDV has been proposed. By using the proposed LDV, the measurement position can be scanned in depth direction without any mechanical movement. The PLC technology is utilized in the proposed design. Using the PLC, in which several optical elements are arranged on a planar surface of a silica or silicon substrate, is a promising way to integrate an optical system in small size. The PLC technology has been widely used for optical passive devices deployed for optical communication systems because of their reliability and ability to be manufactured in large volumes. In this paper, the design and principle of the proposed optical circuit are described. Its characteristics are simulated with a design model based on grating equations for AWGs.

2. Structure

Figure 1 illustrates the optical circuit of the proposed integrated scanning LDV. The circuit is similar to the one we previously proposed [6] except for phase shifter arrays on the arrayed waveguide gratings (AWGs). Input light is split with a 50:50 power splitter. Each light is incident on the slab waveguide of each AWG, phase-shifted through the array, output with diffraction, and incident on the object. The beams are scattered on the object and detected by a photodetector (PD). The beat of the light intensity, depending on the Doppler shift due to the motion of the object, is detected.

Each AWG is used to focus the beam to the object and to diffract the beam whose diffraction angles are changed depending on the wavelength. In other words, the AWGs can function as a lens system and gratings having a planar structure.

Two phase shifter arrays are placed on the waveguide array of the each AWG. One phase shifter array is used for linear change of the phase at the output of the array. This linear change of the phase contributes to the change of the diffraction angle of the beam from the array. Hence, the focusing position in depth direction can be changed by controlling the phase shifter arrays for linear phase change on two AWGs simultaneously. The other phase shifter array is used for parabolic phase change at the output of the array to adjust the focal length. By changing the degree of the parabolic phase change depending on the linear phase change, the measurement volume can be minimized.

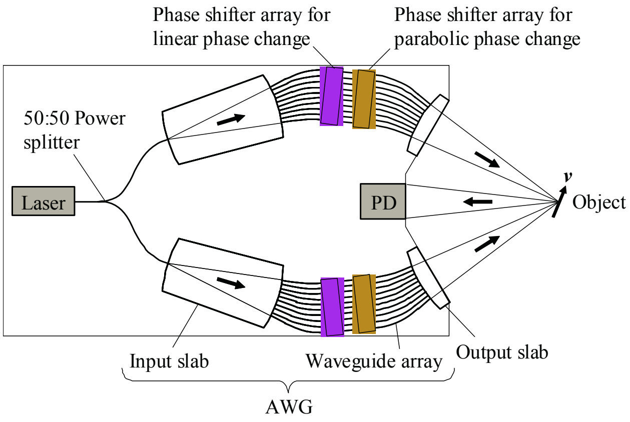

Fig. 1. Optical circuit of the proposed integrated scanning LDV.

3. Principle

In this section, a model of the scanning LDV circuit utilizing the PLC is derived to investigate the characteristics of the circuit. Figure 2 illustrates the schematic diagram of the model of the proposed structure for determining the angles and parameters of AWGs. Here, two AWGs are supposed to have the same design. In Fig. 2, z axis is set to along the direction from the object to the PD and x axis is set to perpendicular to this direction.

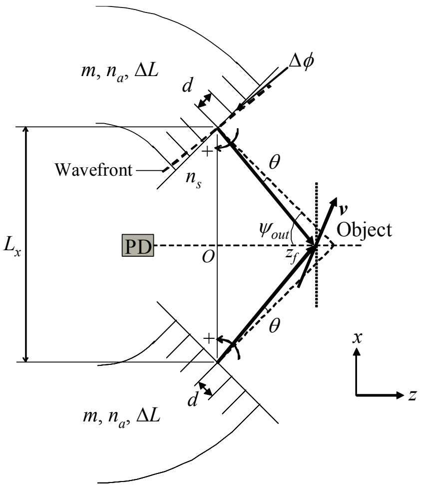

Fig. 2. Model of proposed structure for determining angles and parameters of AWGs.

Let the grating order of two AWGs to be m, the effective refractive indices for the waveguides in the array and slabs to be n_a and n_s, the difference in waveguide length to adjacent waveguides in the array to be ΔL, and the interval of the waveguides in the array at slab-to-array interface to be d. The diffraction angle of the beam from the each AWG, θ, is expressed based on a grating equation [11,12] as

$$\theta = \frac{(m + \Delta\phi/2\pi)\lambda - n_a \Delta L}{n_s d}, \tag{1}$$

where λ is the wavelength and $\Delta\phi$ is the linear phase change, i.e. the difference in phase change between adjacent waveguides in the array induced by the phase shifter array for linear phase change. When the diffraction angle of the beam with the nominal wavelength λ_0 is normally incident to the input size of the array and normally diffracted from the output side of the array, the relation $\lambda_0 = n_a \Delta L/m$ is satisfied. Substituting this relation into Eq. (1) yields

$$\theta = \frac{m(\lambda - \lambda_0) + \Delta\phi\lambda/2\pi}{n_s d}. \tag{2}$$

The output array aperture is directed to the object with the angle of ψ_{out}. The incident angle on the object is then given by $\theta + \psi_{out}$.

The crossing position of the beams from two AWGs, i.e. the measurement position, in depth direction (the z direction) is changed by changing the θ, i.e. by changing the $\Delta\phi$. When the centers of the output sides of two waveguide arrays are separated with the distance of L_x as Fig. 2, the crossing point in the z direction, z_f, is given by

$$z_f = \frac{L_x}{2\tan(\theta + \psi_{out})}. \tag{3}$$

In actual, the phases of the phase shifters for parabolic phase change should be changed, depending on the change of $\Delta\phi$, to focus the beams to the crossing position.

The Doppler shift detected at the PD, F_D, is expressed as

$$F_D = -\frac{1}{2\pi}(\boldsymbol{k}_1 - \boldsymbol{k}_2)\cdot \boldsymbol{v}. \tag{4}$$

where $\boldsymbol{k}_1$ and $\boldsymbol{k}_2$ are the wave vectors of the beam from two AWGs and $\boldsymbol{v}$ is the velocity vector of the object. When the x-component of $\boldsymbol{v}$ is expressed as v_x, Eq. (4) is reduced to

$$F_D = \frac{2v_x \sin(\theta + \psi_{out})}{\lambda}. \tag{5}$$

In the special case that the input wavelength λ is λ_0 and the linear phase change $\Delta\phi$ is zero, the F_D is expressed as the formula typically used in conventional differential LDVs, as

$$F_D = \frac{2v_x \sin\psi_{out}}{\lambda}. \tag{6}$$

By using Eqs. (2), (3) and (5), the proposed scanning differential LDV can be designed.

4. Simulation result and discussion

The basic operation of the proposed LDV is determined under the condition of $\lambda = \lambda_0$ and $\Delta\phi = 0$. Figure 3 plots the beat frequency F_D under this condition as a function of v_x for various ψ_{out}. The nominal wavelength λ_0 is set to 1.3 μm, assuming to use a typical commercial InP-based laser diode as a lightsource and silica materials as waveguides. The result is similar to that of conventional differential LDVs. The ratio F_D/v_x, which can be regarded as the sensitivity for velocity, increases for larger ψ_{out} and smaller λ_0 as discussed in the previous paper [6]. Larger F_D/v_x is desirable to some extent to distinguish signal and drift noise with low frequency due to environmental change when v_x is small. It may be desirable to use 10° or larger for ψ_{out} for $\lambda_0 = 1.3$ μm when the velocity v_x of the object is the order of several tens of μm/s or smaller. On the other hand, it is clear from Eq. (3) that the change of the measurement position z_f is smaller as ψ_{out} increases for the same change of the θ. In the view of a scanning range, therefore, the smaller angle ψ_{out} is desirable. Here, the ψ_{out} is set to 10° hereafter. In this case, F_D/v_x is 0.27 [μm^{-1}].

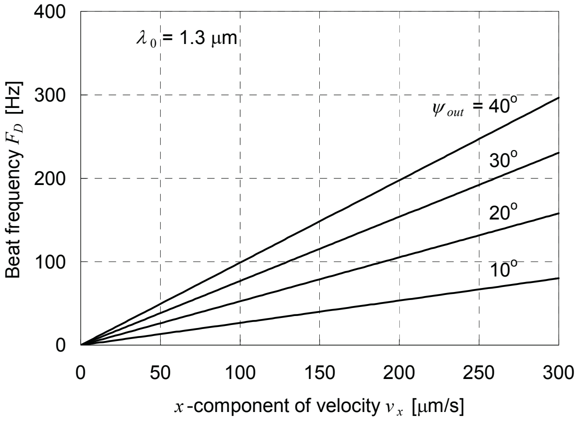

Fig. 3. Beat frequency F_D as function of v_x for various ψ_{out}. $\lambda_0 = 1.3$ μm.

Figure 4 plots the change in the measurement position z_f and the sensitivity F_D/v_x as a function of the diffraction angle θ. Here, the input wavelength λ is set to λ_0 and the ψ_{out} is set to 10°. In typical phase shifters, the maximum phase shift is larger than +/- π rad. It corresponds to the diffraction angle change of about +/- 2.5° when the waveguide interval d is set to 10 μm for example, that is a typical value for silica AWG with a typical relative refractive index Δ of around 1.5 to 2.5% [13-20]. Thus, by programming the control of the phase shifter array so that the phases are linearly aligned at the output of the wavegtuide array, the continuous control of the diffraction angle θ between -2.5° and $+2.5^\circ$ would be achieved. In this case, the measurement position can be changed over the range of -17.4 to +28.9 mm when the L_x is 30 mm. When using the thermooptic (TO) effect for the phase shift in silica materials, the thermal crosstalk between adjacent waveguides should be taken into account in order to control the phase accurately. The use of the structure such as trench structures [21-25] can reduce the thermal crosstalk. The sensitivity F_D/v_x is slightly decreased at the diffraction angle θ of less than zero due to the decrease of the incident angle to the object.

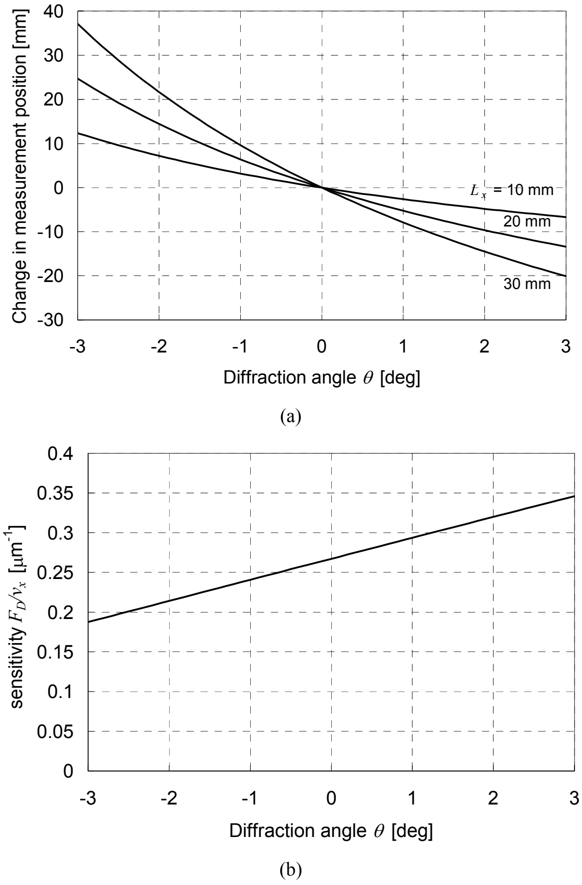

Fig. 4. Change in (a) measurement position z_f and (b) sensitivity F_D/v_x as function of the diffraction angle θ. $\lambda = \lambda_0$ (1.3 μm) and $\psi_{out} = 10^{\circ}$.

The measurement position can be also changed by changing the input wavelength λ as easily understood from Eq. (2). Figure 5 illustrates the configuration of the circuit using a tunable lightsource. In this configuration, the phase shifter array for linear phase change can be eliminated whereas a coherent tunable lightsource such as a tunable laser is needed. From Eq. (2), the change of $\Delta\phi$ corresponds to the change of $2\pi m\lambda/\lambda_0$. Thus, the diffraction angle θ can be changed over the range between -2.5° and $+2.5^{\circ}$ (corresponding to the range in $\Delta\phi$ between $-\pi$ to $+\pi$ rad) when the tuning range of the $m\lambda$ is -0.65 to +0.65 μm. The tuning range of the λ can be reduced as m increases, although the area of the waveguide array is typically enlarged due to the increase of ΔL. For example, when m is set to 20 (around the value typically used in silica-based AWGs for optical communications), the tuning range is -32.5 to +32.5 nm for the change of the θ between -2.5° and $+2.5^{\circ}$.

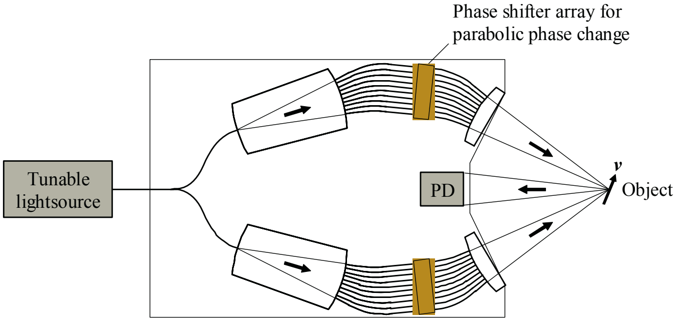

Fig. 5. Configuration of optical circuit using tunable light source.

5. Conclusion

An integrated scanned differential LDV has been proposed using PLC technology. By using the proposed LDV, the measurement position can be scanned in depth direction without any mechanical movement. The PLC technology is utilized in the proposed design for achieving a compact optical circuit. The design and principle of the proposed optical circuit is described, and its characteristics are simulated with a design model based on grating equations for AWGs. The simulation result reveals that the measurement position can be changed over the range of 46 mm in the depth direction without mechanical movement when the displacement between output sides of two waveguide arrays is 30 mm. It would be useful for the velocity measurement in many research and industry.

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